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FOR

TUNING FILTERS HAVING TRANSCONDUCTOR CELLS

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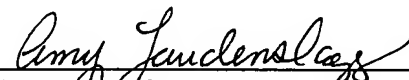*   *   *   *   *

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TUNING FILTERS HAVING TRANSCONDUCTOR CELLS

BACKGROUND OF THE INVENTION

Field of the Invention

5   The present invention relates to electrical signal processing, and, in particular, to continuous-time filters implemented with transconductor cells, such as filters having one or more biquadratic filter sections and filters having ladder structures.

Description of the Related Art

10   Fig. 1 shows a block diagram of a prior-art filter **100** used to generate a filtered electrical output signal **106** from an electrical input signal **102**. Filter **100** has two biquadratic filter sections **104a** and **104b** and a tuning circuit **108**. Filter section **104a** receives and filters input signal **102**. Filter section **104b** receives and further filters the signal generated by filter section **104a** to generate output signal **106**. Tuning circuit **108** provides control signals **110** that control the tuning of filter sections **104a-b**.

15   Fig. 2 shows a block diagram of the architecture of each biquadratic filter section **104** of Fig. 1. As shown in Fig. 2, each biquadratic filter section **104** has four transconductor (gm) cells **202a-d** (having transconductances g_{m1}, g_{m2}, $-g_{m3}$, and $-g_{m4}$, respectively) and two capacitors C1 and C2. The filter section's input signal Vin is received at the input to gm cell **202a**, while the filter section's output signal Vout is presented at the node shared by gm cells **202b** and **202d** and capacitor C2. The biquadratic filter

20   section of Fig. 2 may be said to have an input node **204** (to which gm cell **202a** is connected), an intermediate node **206** (to which capacitor C1 and all four gm cells are connected), and an output node **208** (to which capacitor C2 and gm cells **202b** and **202d** are connected).

Each biquadratic filter section **104** in Fig. 1 implements a pair of corresponding complex poles located in the complex plane at A±Bj, where the Q of the filter section is given by $\sqrt{A^2 + B^2}\big/2A$.

25   Fig. 3 shows a schematic circuit diagram of the architecture of the main components of each transconductor cell **202** of Fig. 2. As shown in Fig. 2, the cell's differential input signal Vin+, Vin- is respectively applied to the gates of transistors M1 and M2. The outputs from current sources I1 and I2 are applied to the drains of M1 and M2, respectively, while the sources of M1 and M2 are both connected to the input of current sink I3. The cell's differential output signal Vout+, Vout- appears at

30   the drains of M1 and M2. Common-mode control circuit **302** samples the differential output signal and generates a control signal **304** for current sink I3, e.g., to maintain a desired common-mode voltage level at Vout+ and Vout- .

Referring again to Fig. 1, tuning circuit **108** of filter **100** has an oscillator **112** consisting of two integrators **114a** and **114b** configured in a loop, where each integrator **114** has a transconductor cell **116** and a capacitor **118**. In addition, tuning circuit **108** has a reference oscillator **120**, a phase detector **122**, and a charge pump/filter **124**. Phase detector **122** compares the reference oscillator's output signal **126**

5 to a signal **128** based on the signal oscillating within oscillator **112** to generate UP or DOWN control signals for charge pump/filter **124**, depending on whether the phase of oscillation signal **128** lags or leads the phase of reference signal **126**. Charge pump/filter **124** accumulates electrical charge corresponding to the UP/DOWN signals from phase detector **122** to generate a tuning control signal **130** used to control the tuning of gm cells **116a-b** to drive the oscillation frequency of oscillator **112** to match that of

10 reference oscillator **120**. As such, tuning circuit **108** functions as a phase-locked loop (PLL).

The electrical characteristics of transconductor cells **116a-b** and capacitors **118a-b** are specifically selected to replicate as closely as possible the electrical characteristics of each biquadratic filter section **104** in the main signal path of filter **100**. As such, the same control signal (**130**) used to control the tuning of gm cells **116a-b** in oscillator **112** is also applied as control signals **110** to control the

15 tuning of gm cells in each biquadratic filter section **104** (as indicated in both Figs. 1 and 2).

Although not shown in the figures, an amplitude detector is often employed within tuning circuit **108** to monitor the amplitude of the signal oscillating within oscillator **112** to adjust the output conductance of each gm cell in order to maintain a constant, desired oscillator amplitude. This can provide accurate tuning of the Q of each biquadratic filter section **104** in filter **100**.

20 Notwithstanding the general operability of filter **100**, errors will typically result from a number of sources, including differences in parasitic capacitances at the transconductor cell output nodes, random component mismatch, and differences in cell loading. In addition, the reference oscillator in the tuning circuit can create interference with the signal being filtered in the main signal path.

25 SUMMARY OF THE INVENTION

Problems in the prior art are addressed in accordance with the principles of the present invention by providing, in one exemplary embodiment, circuitry comprising a filter having one or more filter · sections, wherein at least one of the one or more filter sections comprises a plurality of transconductor (gm) cells. At least one of the gm cells can be configured to have substantially zero transconductance,

30 such that the at least one filter section will oscillate.

BRIEF DESCRIPTION OF THE DRAWINGS

Other aspects, features, and advantages of the present invention will become more fully apparent from the following detailed description, the appended claims, and the accompanying drawings in which like reference numerals identify similar or identical elements.

Fig. 1 shows a block diagram of a prior-art filter having two biquadratic filter sections;

Fig. 2 shows a block diagram of the architecture of each biquadratic filter section of Fig. 1;

Fig. 3 shows a schematic circuit diagram of the architecture of each transconductor cell of Fig. 2;

Fig. 4 shows a block diagram of a filter having biquadratic filter sections, according to one embodiment of the present invention;

Fig. 5 shows a block diagram of the tuning circuit of Fig. 4;

Fig. 6 shows a schematic circuit diagram of the architecture of the main components of the third transconductor cell of the biquadratic filter section of the tuning circuit of Fig. 4;

Fig. 7 shows a filter having biquadratic filter sections, according to an alternative embodiment of the present invention;

Fig. 8(a) shows a block diagram of a filter having a ladder structure, according to one embodiment of the present invention; and

Fig. 8(b) shows a block diagram of a resonator of the filter of Fig. 8(a).

DETAILED DESCRIPTION

The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments necessarily mutually exclusive of other embodiments.

Preferred embodiments of the present invention employ a technique for tuning filters implemented with transconductor cells, such as filters having biquadratic filter sections and filters having ladder structures. According to one embodiment of this technique, a biquadratic filter section is designed to support both a filter mode (in which the section functions as a conventional filter) and a tuning mode (in which the section oscillates and can be tuned to achieve a desired cutoff frequency). In one application, a biquadratic filter section of the present invention is configured to operate as the tuning circuit for a filter having a main signal path with one or more instances of analogous biquadratic filter sections. In another application, each filter section in the main signal path of a filter is implemented using an instance of a biquadratic filter section of the present invention including tuning circuitry that enables each filter section to tune itself. The present invention can also be implemented in the context of other types of filters implemented using transconductor cells, such as filters with ladder structures.

The present invention can provide filters having lower power dissipation, more accurate tuning, and reduced interference as compared with prior-art filters, such as those based on the architecture of Fig. 1.

5   <u>Exemplary Filters having Biquadratic Filter Sections</u>

Fig. 4 shows a block diagram of a filter **400**, according to one embodiment of the present invention. Filter **400** has a main signal path comprising one or more biquadratic filter sections **404**, where the main signal path receives an input signal **402** and generates the filtered output signal **406**, where the output from each biquadratic filter section provides the input to the next biquadratic filter

10   section along the main signal path. Each biquadratic filter section **404** has the same general architecture as that shown in Fig. 2. Filter **400** also has a tuning circuit **408**, which provides tuning signals **410** to each biquadratic filter section **404** along the main signal path.

Fig. 5 shows a block diagram of tuning circuit **408** of Fig. 4. As shown in Fig. 5, tuning circuit **408** has, among other elements to be discussed later on, a biquadratic filter section **510**, which also has

15   the same general architecture as that shown in Fig. 2. In addition, with the sole exception of the third transconductor cell of biquadratic filter section **510** of tuning circuit **408** (corresponding to gm cell **202c** of Fig. 2), each transconductor cell of each biquadratic filter section (i.e., section **510** of Fig. 5 and sections **404** of Fig. 4) in filter **400** has the same general architecture as that shown in Fig. 3.

Fig. 6 shows a schematic circuit diagram of the architecture of the main components of the third

20   transconductor cell of biquadratic filter section **510** of tuning circuit **408** of Figs. 4 and 5. In addition to all of the elements shown in Fig. 3, this third gm cell has a set of switches **602** that can be selectively configured to apply either (a) the differential input signal Vin+, Vin- to the two gm cell inputs, respectively, or (b) the common-mode voltage signal Vcm to both gm cell inputs. When the differential input signal Vin+, Vin- is selected, the third transconductor cell operates in the same (i.e., filter mode)

25   manner as the other third transconductor cells of the other biquadratic filter sections (i.e., sections **404**). However, when the common-mode voltage signal Vcm is selected, biquadratic filter section **510** of tuning circuit **408** will oscillate at a frequency corresponding to the filter section's cutoff frequency when the filter section is operated in its filter mode.

This can be demonstrated mathematically. In particular, the transfer function for a biquadratic

30   filter section having an architecture as shown in Fig. 2 is given by Equation (1) as follows:

$$\frac{Vout}{Vin} = \frac{g_{m1}}{g_{m4}} * \frac{\dfrac{g_{m2}g_{m4}}{C_1C_2}}{s^2 + s\dfrac{g_{m3}}{C_1} + \dfrac{g_{m2}g_{m4}}{C_1C_2}} , \qquad (1)$$

where the cutoff frequency ω_0 and the Q of the biquadratic filter section are given by Equations (2) and (3) as follows:

$$\omega_0 = \sqrt{\frac{g_{m2}g_{m4}}{C_1C_2}} \qquad (2)$$

$$Q = \sqrt{\frac{g_{m2}g_{m4}}{g_{m3}}} \sqrt{\frac{C_1}{C_2}} . \qquad (3)$$

Referring again to Fig. 6, when the common-mode voltage signal Vcm is applied to the inputs of the third gm cell of biquadratic filter section **510**, the transconductance g_{m3} of that third gm cell goes to zero, which, according to Equation (3) makes the Q of filter section **510** go to infinity. This effectively moves the poles of filter section **510** to the $j\omega$ **j** axis (as indicated by replacing the g_{m3} term in Equation (1) with 0), which in turn allows filter section **510** to oscillate and, in particular, to oscillate at the cutoff frequency ω_0. Note that, although the transconductance of the third gm cell is set to zero for the oscillation mode, the loading at all nodes of filter section **510** is approximately the same as when the third gm cell is operated in its filter mode.

Referring again to Fig. 5, in addition to biquadratic filter section **510**, tuning circuit **408** has components that assist in the generation of tuning control signals **410** of Fig. 4. For example, programmable controller **502** loads timer **504**, counter **506**, and tuning control block **508** with appropriate address and data information and implements a tuning algorithm. In particular, programmable controller **502** applies oscillate control signal **516** and tuning vector **518** to biquadratic filter section **510** and receives borrow signal **520** from counter **506**. Depending on the implementation, tuning vector **518** controls such characteristics as transconductance, capacitance, and source degeneration to adjust the frequency of oscillation of biquadratic filter section **510**. Although not shown in Fig. 5, control signals

410 of Fig. 4 are identical to tuning vector **518** or at least are generated based on some or all of the information represented in tuning vector **518**.

When dictated by controller **502**, tuning control block **508** applies oscillate control signal **516** to biquadratic filter section **510** to control switches **602** in the third gm cell (see Fig. 6) to select the common-mode voltage signal Vcm to cause filter section **510** to oscillate. The output of biquadratic filter section **510** is sliced at comparator **512**, whose output is applied to gate **512** along with the output from timer **504** to generate the input to counter **506**. Timer **504** is set to a desired measurement period, while counter **506** is preset to the target number of oscillation cycles for the desired filter cutoff frequency ω_0 that should occur during the measurement period. If, at the end of the timer period, a borrow has occurred, then there were more oscillation cycles than desired, and controller **502** adjusts the tuning vector to a lower value. If no borrow occurs, then controller **502** adjusts the tuning vector to a higher value. In this way, programmable controller **502** ensures that biquadratic filter section **510** will oscillate at the desired cutoff frequency ω_0. In addition, Q tuning can be accomplished by adjusting the output conductance of the gm cells within filter section **510** to achieve a desired oscillation amplitude.

In a preferred implementation, tuning vector **518** represents a set of digital control signals that can be stored in flip-flop circuitry within tuning control block **508**. As such, the tuning of biquadratic filter section **510** can be implemented intermittently as opposed to the continuous tuning of prior-art filter **100** of Fig. 1. This can reduce the power consumption of filter **400** of the present invention as compared to that of prior-art filter **100**. In addition, filters of the present invention can avoid having to implement the reference generator and phase-locked loop of prior-art filter **100**.

Because biquadratic filter section **510** of Fig. 5 (preferably) has the same general architecture as each biquadratic filter section **404** in the main signal path of filter **400** of Fig. 4, filter section **510** can be -- and preferably is -- implemented as a replica that more closely matches the filter sections in the main signal path than can be achieved using oscillator **112** of prior-art filter **100** of Fig. 1. As such, the errors associated with such sources as differences in parasitic capacitances at the transconductor cell output nodes, random component mismatch, and differences in cell loading can be reduced.

Fig. 7 shows a filter **700**, according to an alternative embodiment of the present invention. As shown in Fig. 7, and like filter **400** of Fig. 4, filter **700** has a main signal path comprising one or more biquadratic filter sections **704**, where the main signal path receives an input signal **702** and generates the filtered output signal **706**, where the output from each biquadratic filter section provides the input to the next biquadratic filter section along the main signal path. Like filter **400**, each section **704** in filter **700** has a biquadratic filter having the same general architecture as that shown in Fig. 2. Unlike filter **400**,

however, filter **700** does not have a separate tuning circuit outside of the main signal path. Rather, in filter **700**, each section **700** is itself an instance of tuning circuit **408** having tuning elements as shown in Fig. 5 and a biquadratic filter section **510**, whose third gm cell is shown in Fig. 6.

In this embodiment, each quadratic filter section **704** can tune itself without having to rely on any replica. Moreover, each filter section **704** can be implemented to perform its tuning algorithm independent of each other filter section **704**. Since each filter section **704** is able to store its own tuning vector, depending on the particular application, the tuning of different filter sections can be selected to be either simultaneous or staggered in time, whichever is more desirable in terms of minimizing the impact to normal filtering operations.

Exemplary Filters having Ladder Structures

In the previous section, the present invention was described in the context of filters having one or more biquadratic filter sections in the filter's main signal path. In this section, the present invention is described in the context of filters having a ladder structure.

Fig. 8(a) shows a block diagram of a filter **800** having a ladder structure, according to one . embodiment of the present invention. Fig. 8(b) shows a block diagram of resonator RES no. 1 of filter **800**. According to this embodiment, transconductor cell g_{md} of Fig. 8(b) is implemented using the same gm cell architecture as shown in Fig. 6. Filter **800** can be configured as an oscillator by switching off transconductor cell g_{md} of Fig. 8(b) (i.e., by configuring switches **602** of Fig. 6 such that the common-mode voltage signal Vcm is applied to both gm cell inputs).

In one implementation, filter **800** can be used in place of biquadratic filter section **510** of Fig. 5 to form a ladder tuning circuit that is analogous to biquadratic tuning circuit **408** of Fig. 4. In a configuration analogous to that shown for filter **400** of Fig. 4, this ladder tuning circuit can be used to tune the main signal path of a filter having a ladder structure such as that shown in Fig. 8(a). Alternatively, in a configuration analogous to that shown for filter **700** of Fig. 7, this ladder tuning circuit can be part of the ladder filter's main signal path.

The present invention has been described in the context of filters having biquadratic filter sections and filters having ladder structures. Both of these types of filters are implemented using transconductor cells. The present invention can be extended to apply to other suitable types of filters that are implemented using transconductor cells.

The present invention may be implemented as circuit-based processes, including possible implementation as a single integrated circuit (such as an ASIC or an FPGA), a multi-chip module, a single card, or a multi-card circuit pack. As would be apparent to one skilled in the art, various functions

of circuit elements may also be implemented as processing steps in a software program. Such software may be employed in, for example, a digital signal processor, micro-controller, or general-purpose computer.

It will be further understood that various changes in the details, materials, and arrangements of the parts which have been described and illustrated in order to explain the nature of this invention may be made by those skilled in the art without departing from the scope of the invention as expressed in the following claims.

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